Development and Testing of a Refractory Millimeter-Wave Absorbent Heat Exchanger

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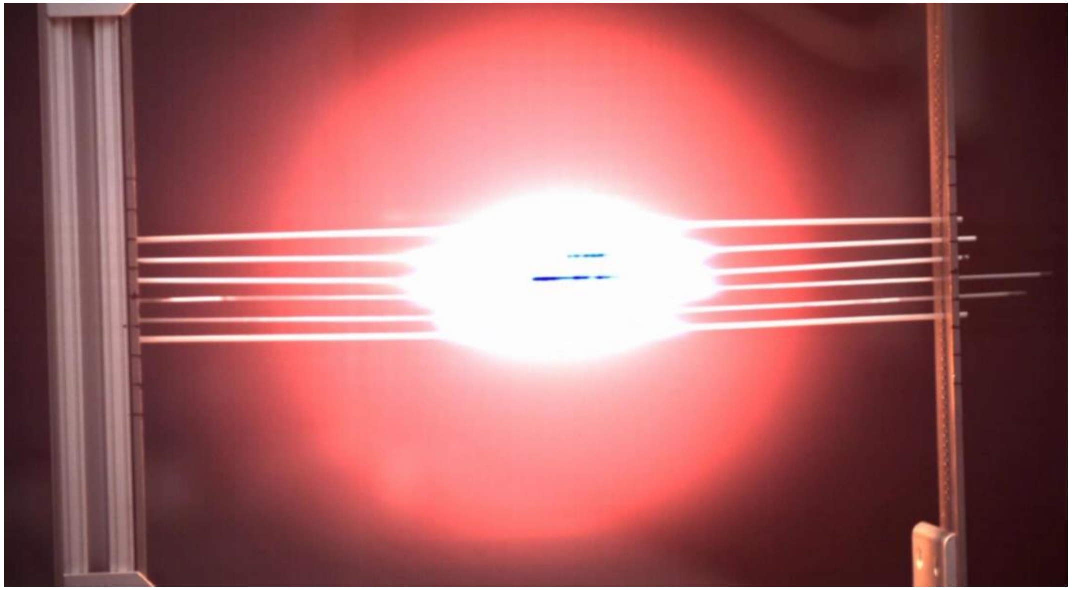

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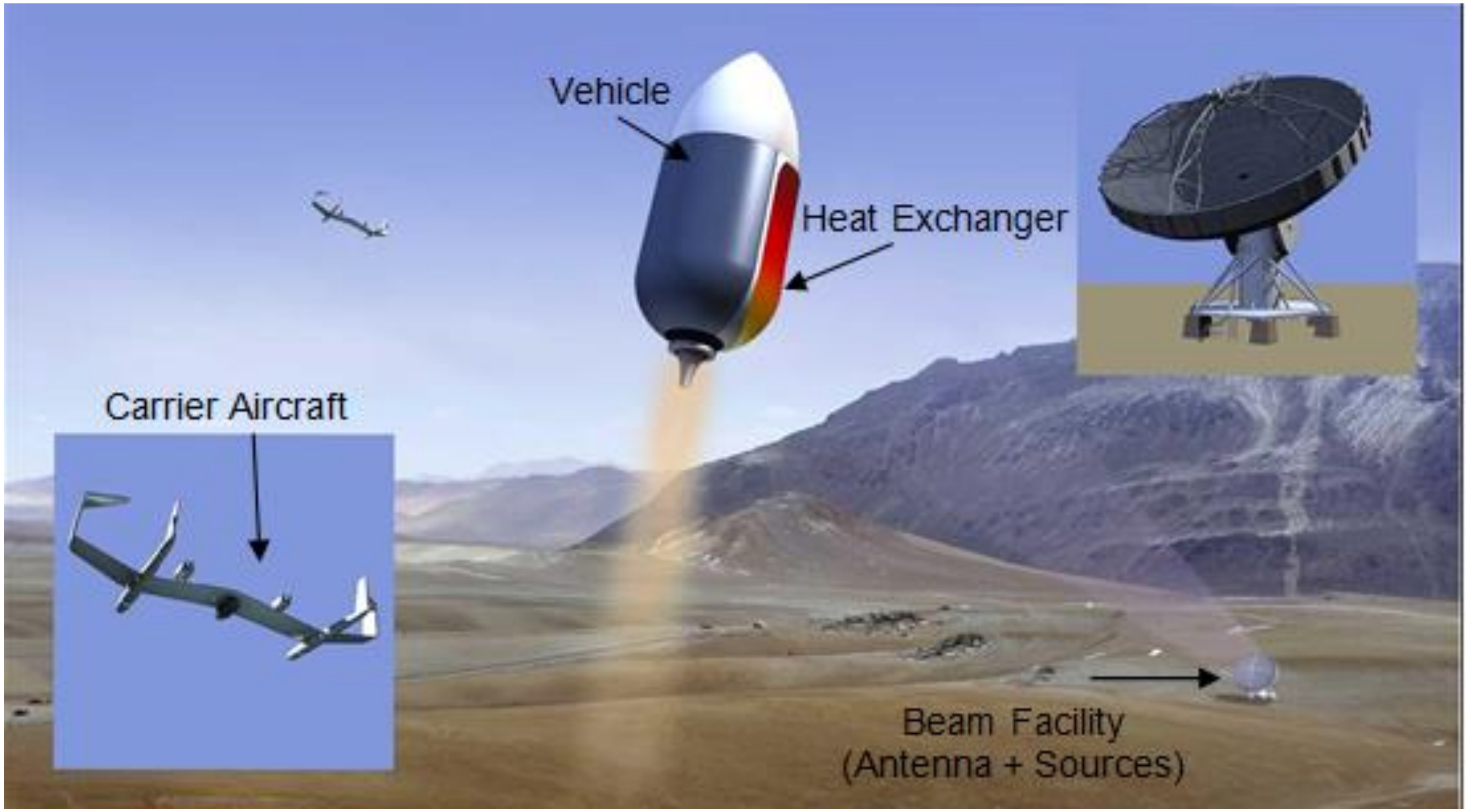
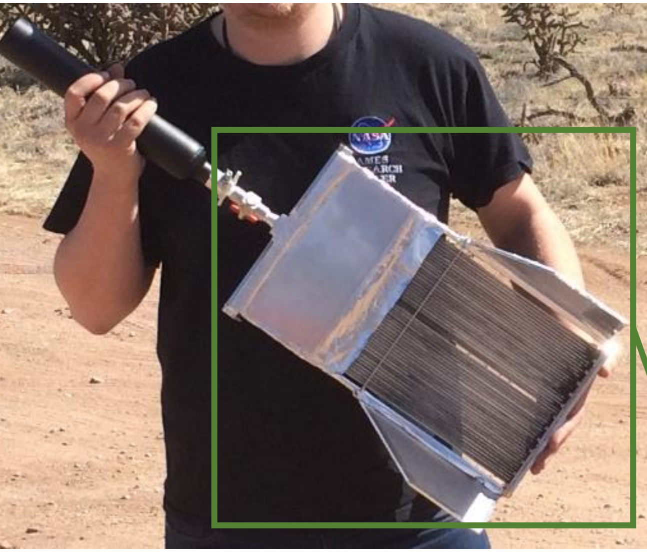
The Millimeter-wave Thermal Launch System (MTLS)



Artist view of the MTLS concept

Thermal propulsion using beamed energy as the source of power

The planar heat exchanger: point of design

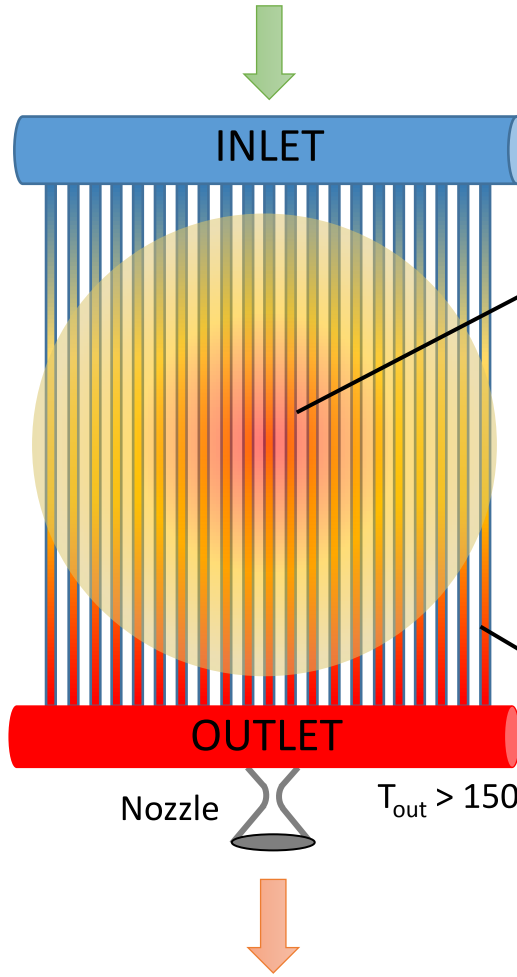


Requirements:

- Absorb the mm-wave beam
- Transfer heat efficiently to propellant
- Withstand high temperature (> 1500 K)
- Lightweight

Propellant: Nitrogen, Argon

T_{in} = 300 K
P_{in} = 6 bar



Millimeter-wave beam
Gaussian distribution 20 cm Ø
30 kW absorbed in HX

T_{out} > 1500 K

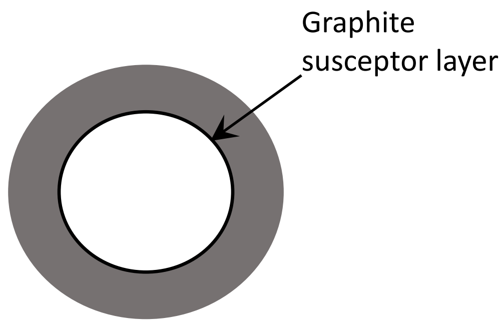
Expanded gas

Small diameter ceramic tubes
Transparent to mm-wave

→ **Use of coatings**

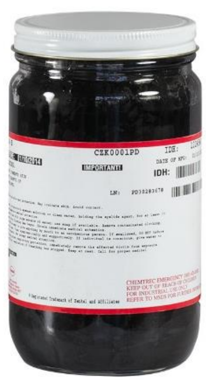
Solution: Internal graphite coating

- Coating on the internal part of the tube
  - Non-oxidizing atmosphere
  - Heat source is next to the flow



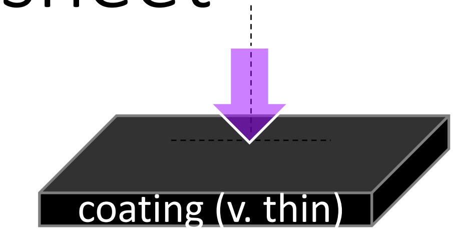
Tube cross-section

- Use of “Aquadag”: A resistance paint
  - Composed of colloidal graphite in solution with water
  - Ohms per square of the coating are tuned by adjusting the mixture ratio

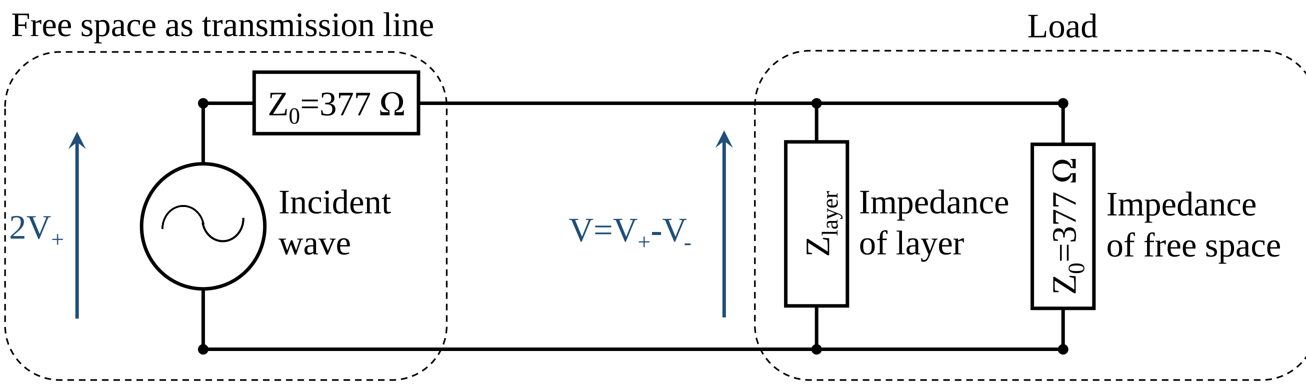


- Tubes are coated by using a pump system that flows the coating through the tube
  - Cured in a vacuum oven for 3 hours
  - Multiple coatings give best uniformity

Absorption by a thin conducting sheet

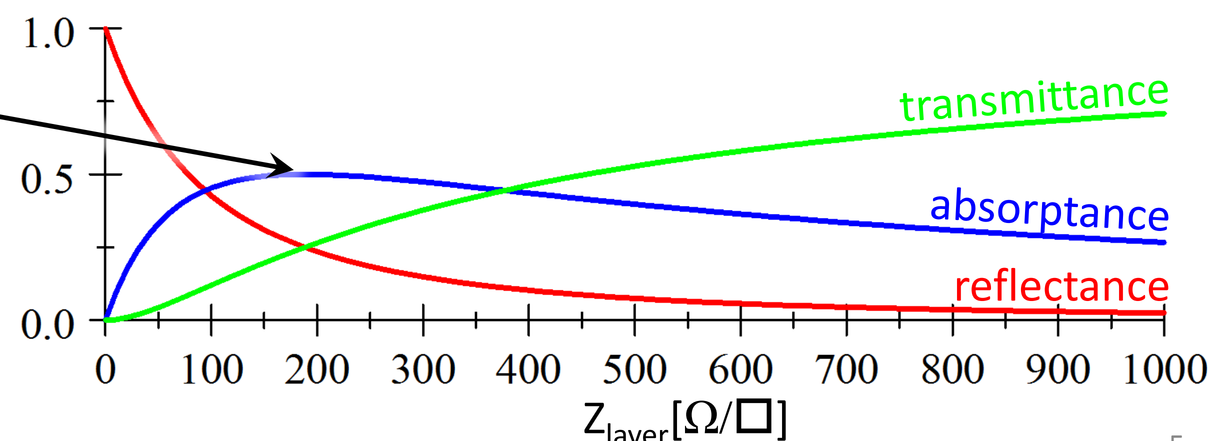


- Thévenin equivalent circuit
  - Transmission line model of reflection for planar conducting sheet in free space illuminated at normal incidence by an incident wave



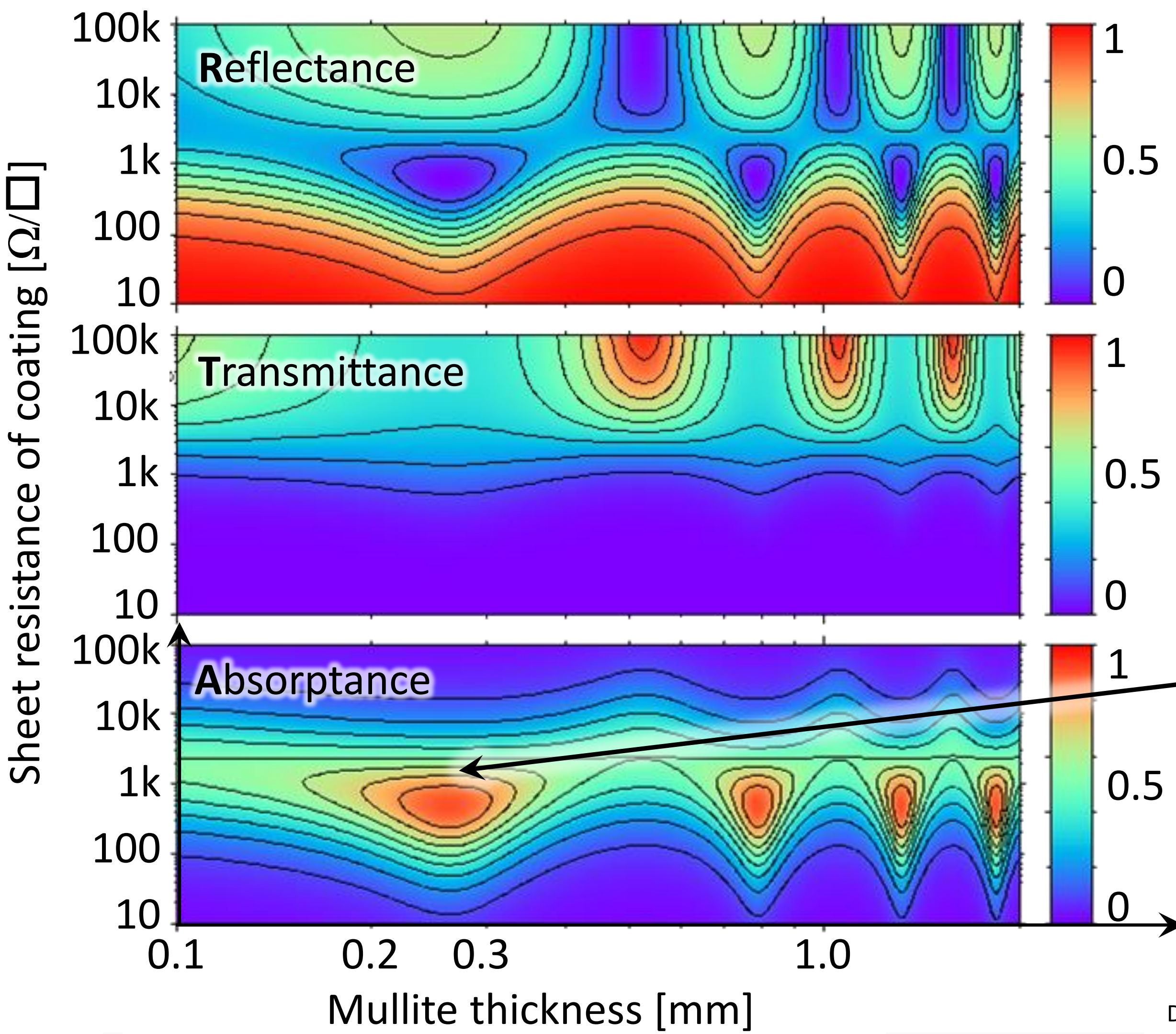
- Based on this circuit, and defining $r = \frac{Z_{layer}}{Z_0}$, it can be shown that:
  - Absorptance $A = \frac{r}{\left(r+\frac{1}{2}\right)^2}$, Reflectance $R = \frac{1}{(1+2r)^2}$, Transmittance $T = \frac{r^2}{\left(r+\frac{1}{2}\right)^2}$

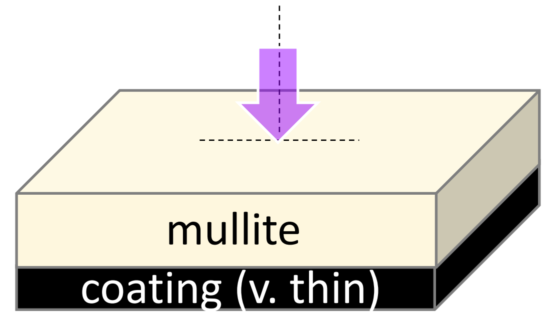
A **maximum of 50%** of the incident power can be absorbed by a sheet on its own



Planar stratified layer

- The stratified layer model can include the mullite 'anti-reflection' layer. Predictions for normal incidence are shown here.





Up to 90% absorption around 0.2-0.3 mm (1/4 wavelength thick and multiples thereof) and 100-1,000 Ω/☐.

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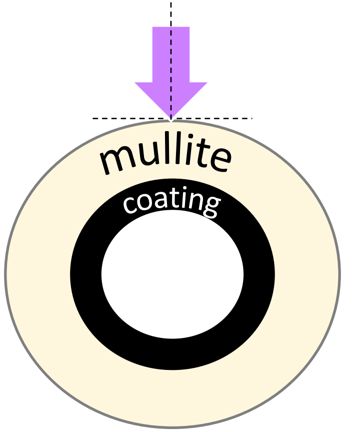
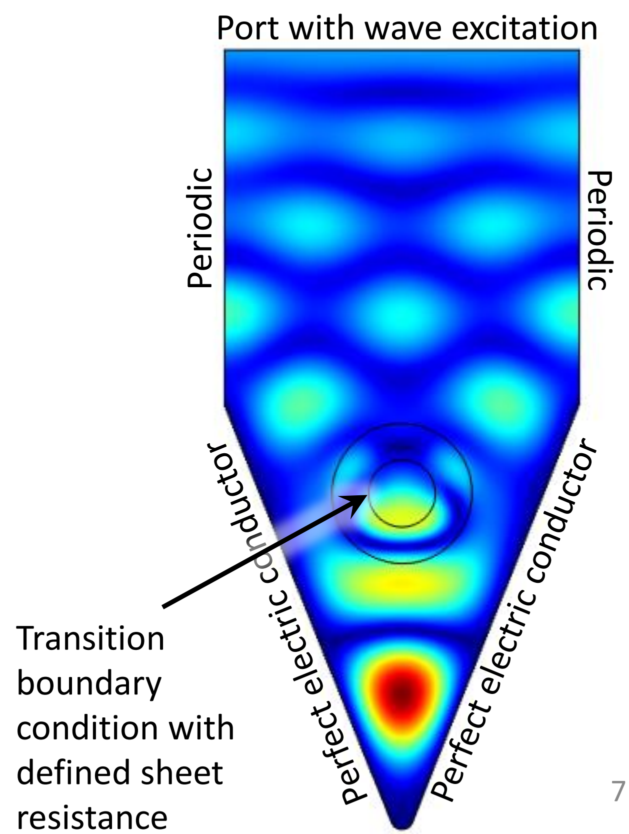
Finite element

- In reality, the tube is curved
- The tube is at wavelength scale
- The tube is not isolated, but in an array
- Can a back-reflector be contoured to improve absorption, uniformity of heating around the tube (to reduce transient bending)?

- **Work is still underway in COMSOL to address these questions**
- We want to produce performance maps, similar to those just shown for the stratified layer model, and compare them to experimental results.
- The example shows norm of electric field for wave incident on tube with interior coating and V shaped back-reflector

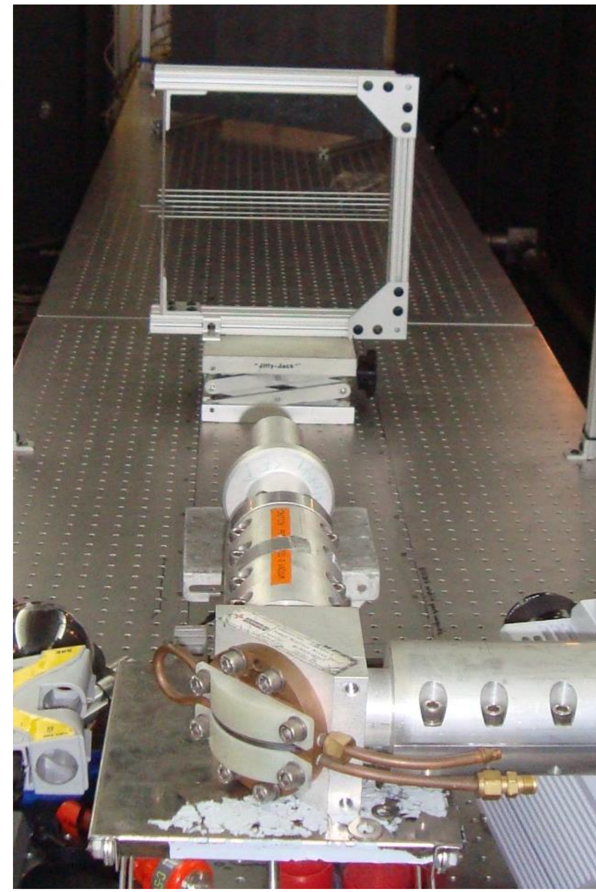


Tube cross-section



Coating experiments at General Atomics DIII-D facility

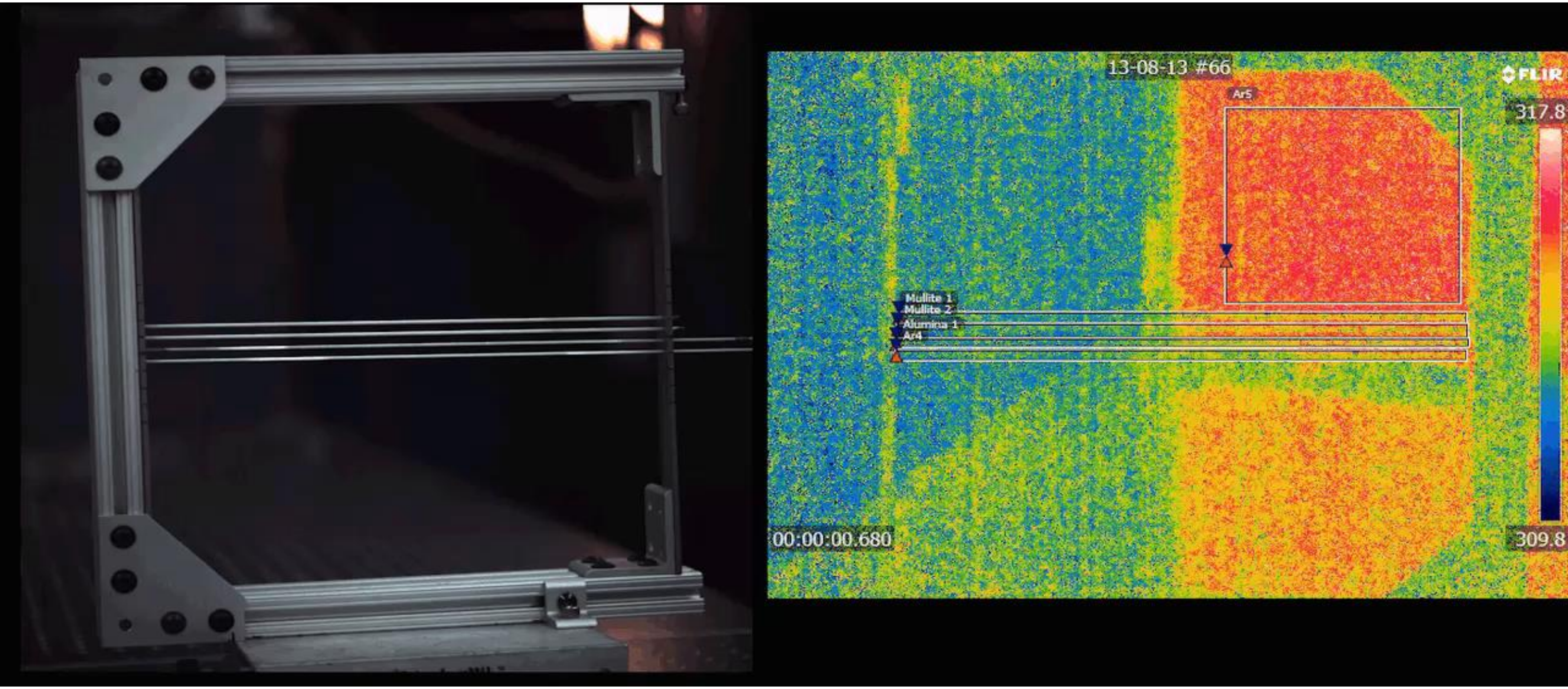
- Test campaigns at General Atomics in our Mobile Test Unit (MTU) to investigate absorptivity of materials
  - Use of 110 Ghz gyrotron at DIII-D facility
  - Test of material coupons, coated tubes, concentrating mirrors, …



Initially: tubes beamed for 50 to 1000 ms at peak power intensity of 1-2kW/cm^2

After refinement: tubes beamed up to 3s at 250 to 530 W/cm^2

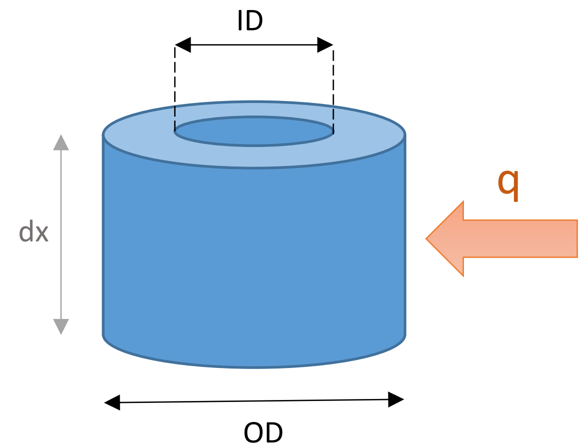
Example of tube testing



Mullite and Alumina tubes with internal Aquadag coating (mixture ratio 1:1)
Maximum temperature reached: 1650 K

Tube broken due to non uniformity of coating

Absorption results



- Consider the beaming of a tube section *dx* with an inner diameter *ID* and outer diameter *OD*
- Simplifications:
  - Beam absorbed uniformly throughout the mass
  - Section at uniform temperature $T = T_{max}$
  - Assume power density *q* from the incident beam is uniform on the section
  - Graphite layer weight and specific heat capacity are neglected
- Heating rate if the tube was a black body:

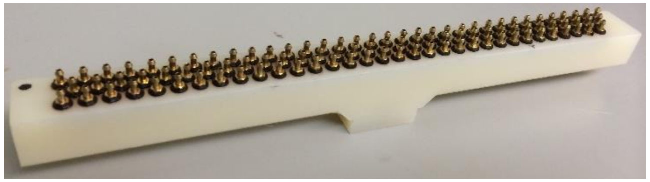
$$\left.\frac{dT}{dt}\right|_{\substack{black\\body}} = 4\,\frac{q}{c_p(T)\,\rho}\,\frac{OD}{\pi\,(OD^2 - ID^2)}$$

$$A = \frac{\left. {}^{dT}\!/_{dt}\right|_{measured}}{\left. {}^{dT}\!/_{dt}\right|_{black\ body}}$$

- Campaign results (preliminary, work still in progress!)

Tube type		**Absorptance A [-]**
Alumina 0.794 mm ID, 0.39 mm wall	Uncoated	0.02
	Coated with 1:1 mix ratio	0.22 … 0.28
Mullite 0.794 mm ID, 0.39 mm wall	Uncoated	0.08
	Coated with 1:1 mix ratio	0.25 … 0.5 (?)
Mullite 1.19 mm ID, 0.395 mm wall	Uncoated	0.05
	Coated with 1:1 mix ratio	0.45 … 0.58

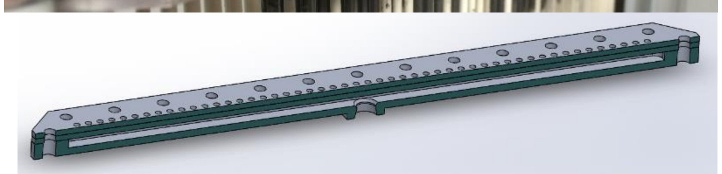
The heat exchanger assembly



Nylon inlet manifold with barbed fittings

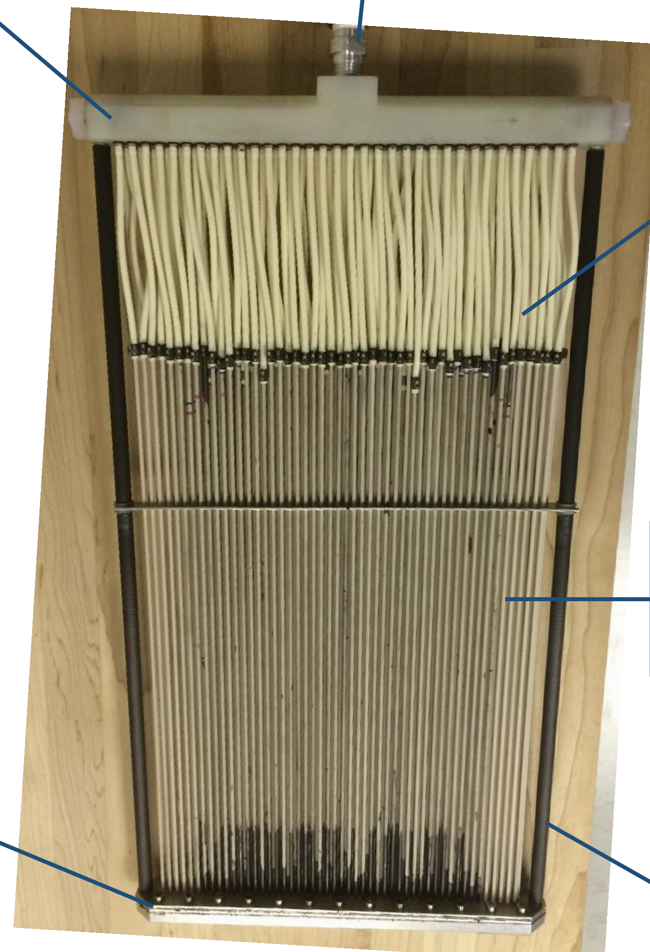
Flow-restricting orifice

Polyurethane tubing with crimped clamp



Flanged titanium outlet with graphite gasket

Carved nozzle: $\varnothing_t$ = 7.6cm and $\frac{A_E}{A_t} = 1.5$



100 Mullite tubes
1.19 mm ID, 0.395 mm wall
Coated with Aquadag

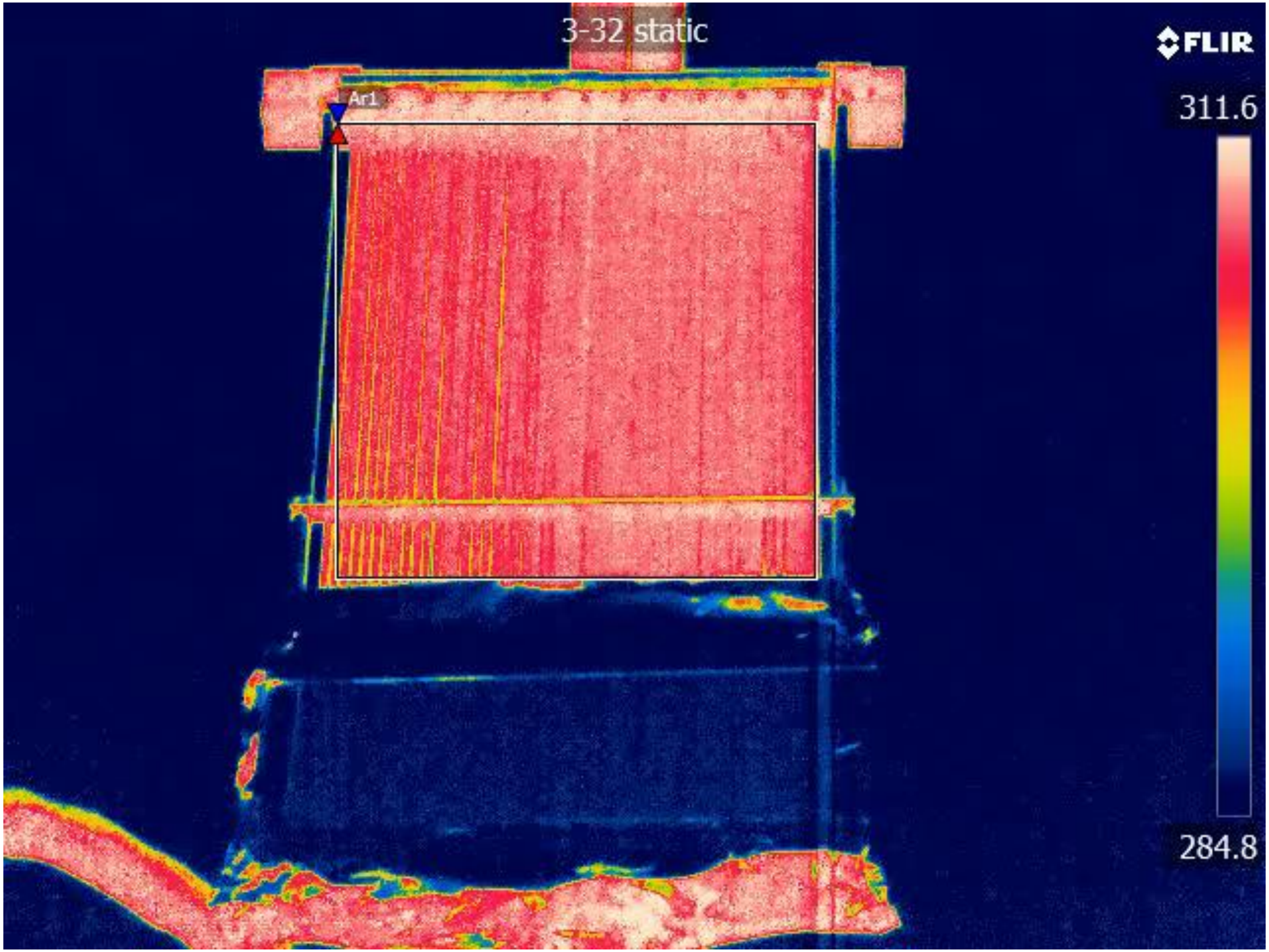
Carbon fiber tube (strut)

Test Arrangement

- Testing using 100 kW-class W-band source
  - Gaussian-like beam focused onto heat exchanger
  - Point and tracking system off for static test
  - Pre-heating of heat exchanger using the beam
  - **6 to 10 s** total shot duration
  - Use of **Argon** for propellant

- Shot parameters
  - Power peak intensity of **71 W/cm^2**
  - **33 kW** in a 30 cm Ø bucket

Static test using a 3-32” orifice with Argon



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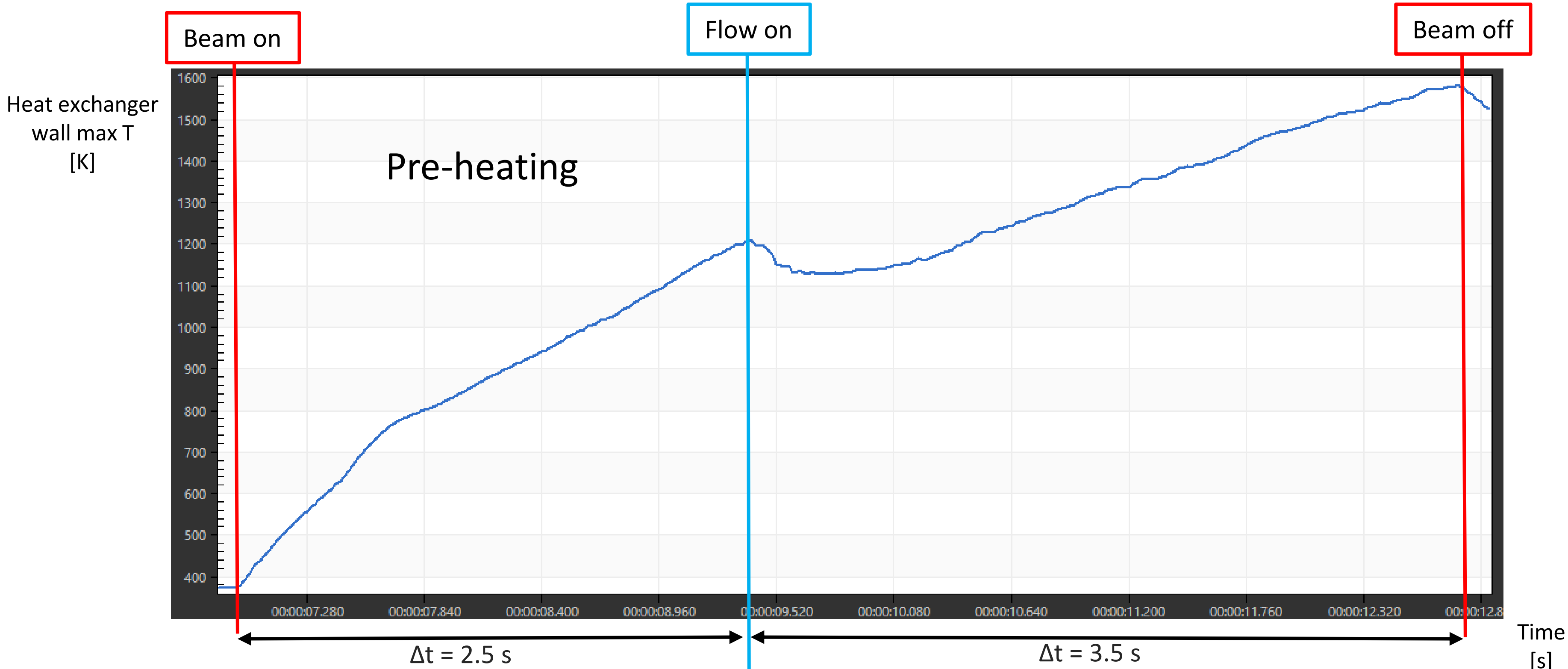
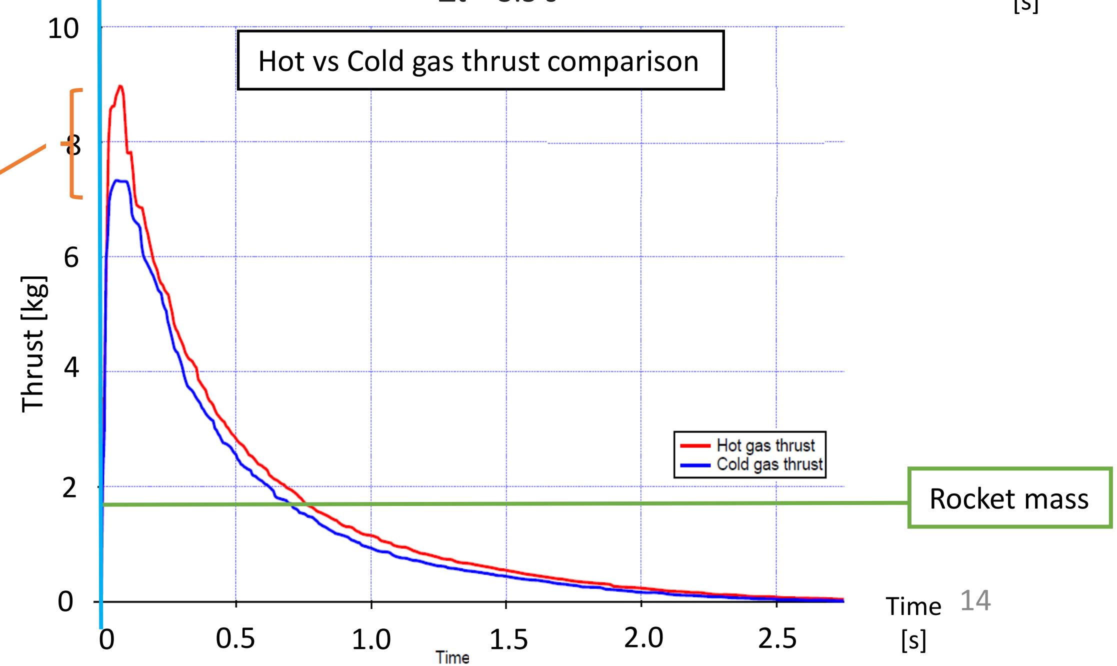
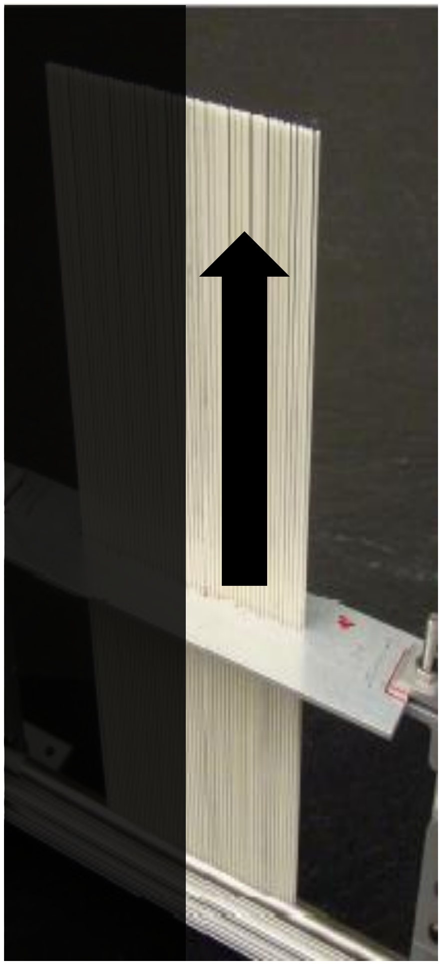


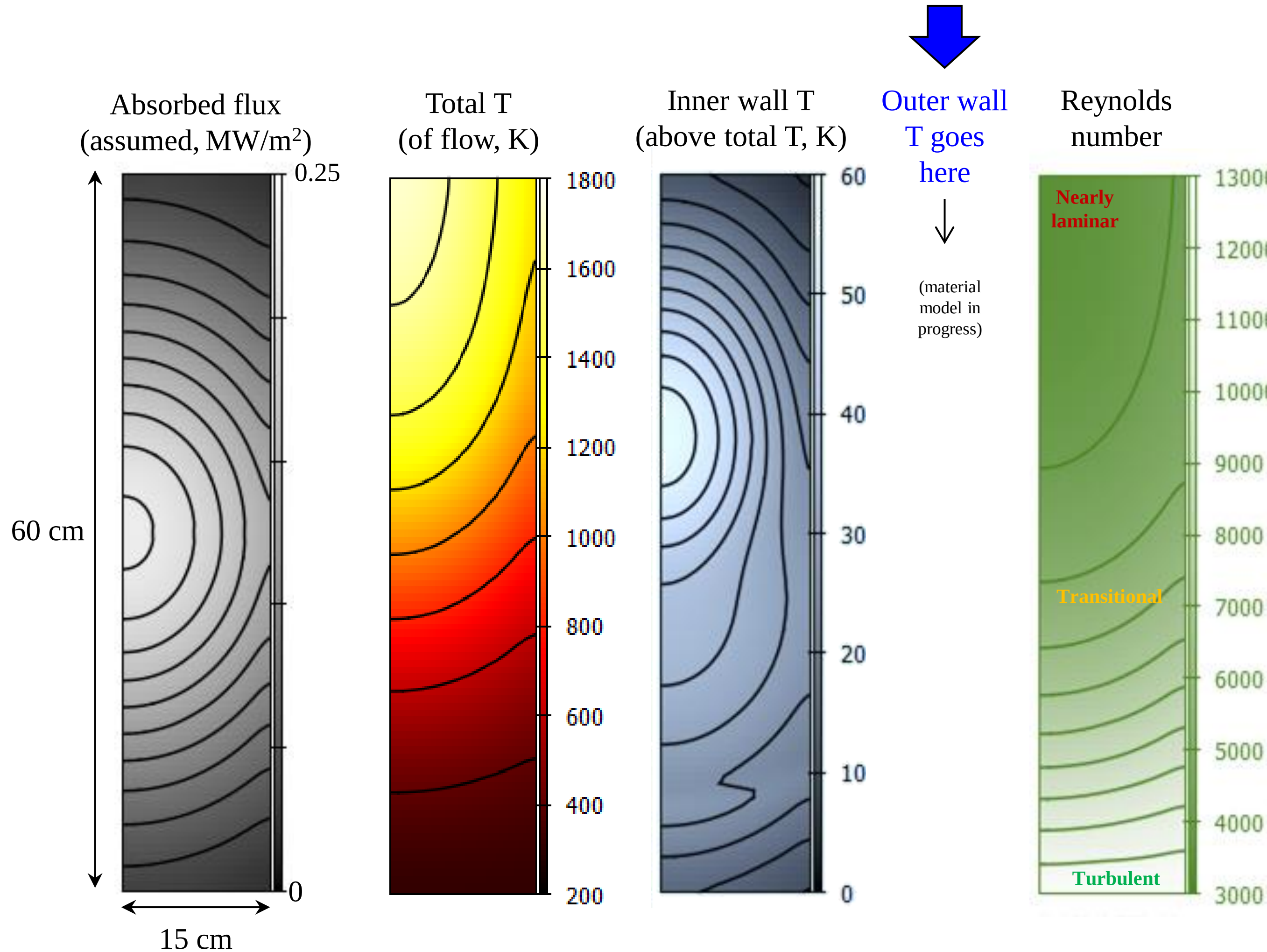
25 % increase in thrust when comparing test with and without the beam on
→ Heat transfer to investigate …



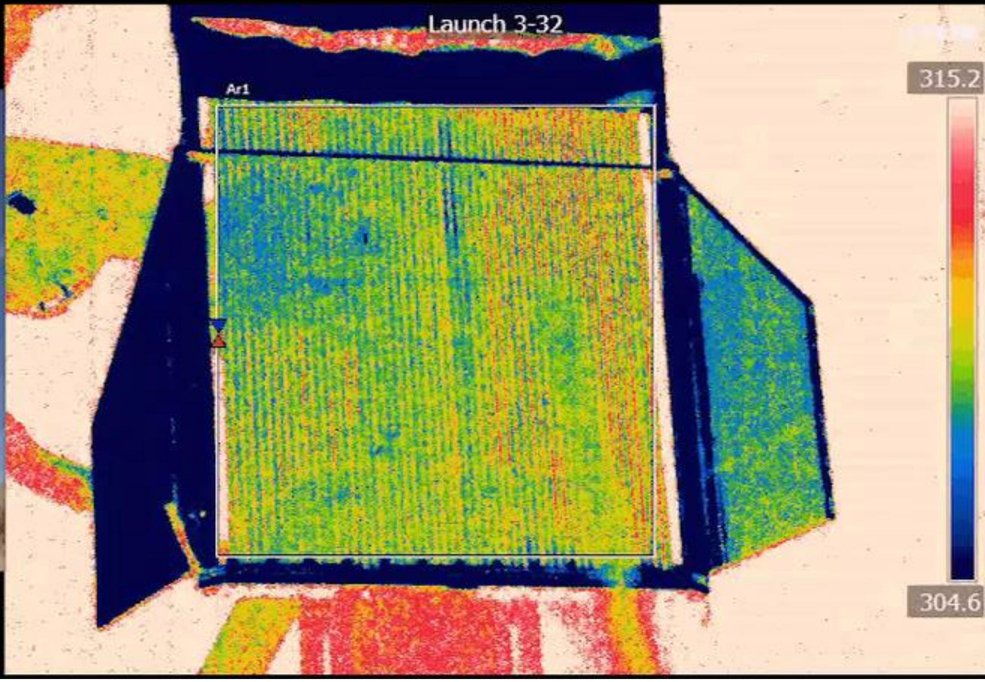
Steady state not reached as mass flow rate is not constant

Quasi-1D simulations



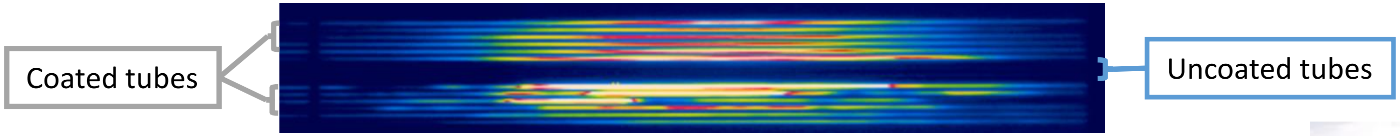


First flight of MM-wave rocket



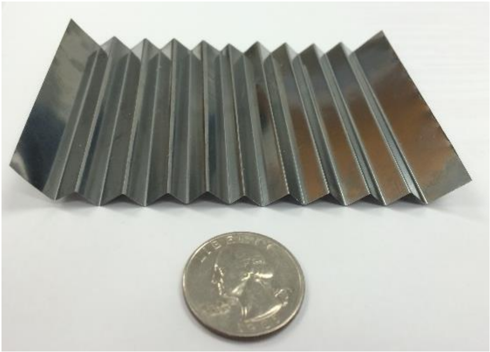
Highlights & Future work

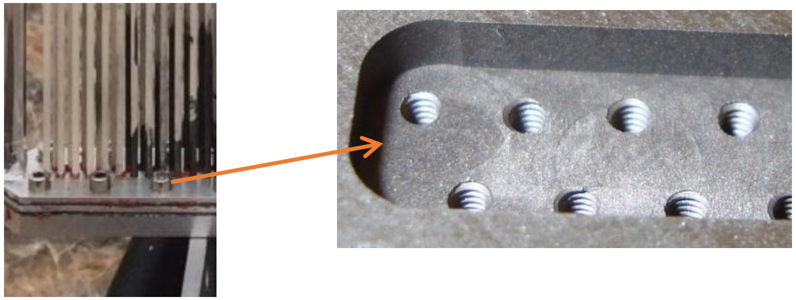
- Achievements
  - Using a graphite coating, we turned mm-wave transparent ceramic into an absorber



  - Tube surface temperatures higher than 1700 K
    (1500 K with flow of helium) were reached without damaging tubes
  - Heat exchanger prototypes were assembled, static tested and launched

- Future optimization
  - Improve coating quality (absorptance and uniformity)
  - Improve convective heat transfer and absorption efficiency
  - Conduct finite element absorption simulation
  - Investigate foil backing concentrator, threaded tubes,
    other materials for higher temperatures, …

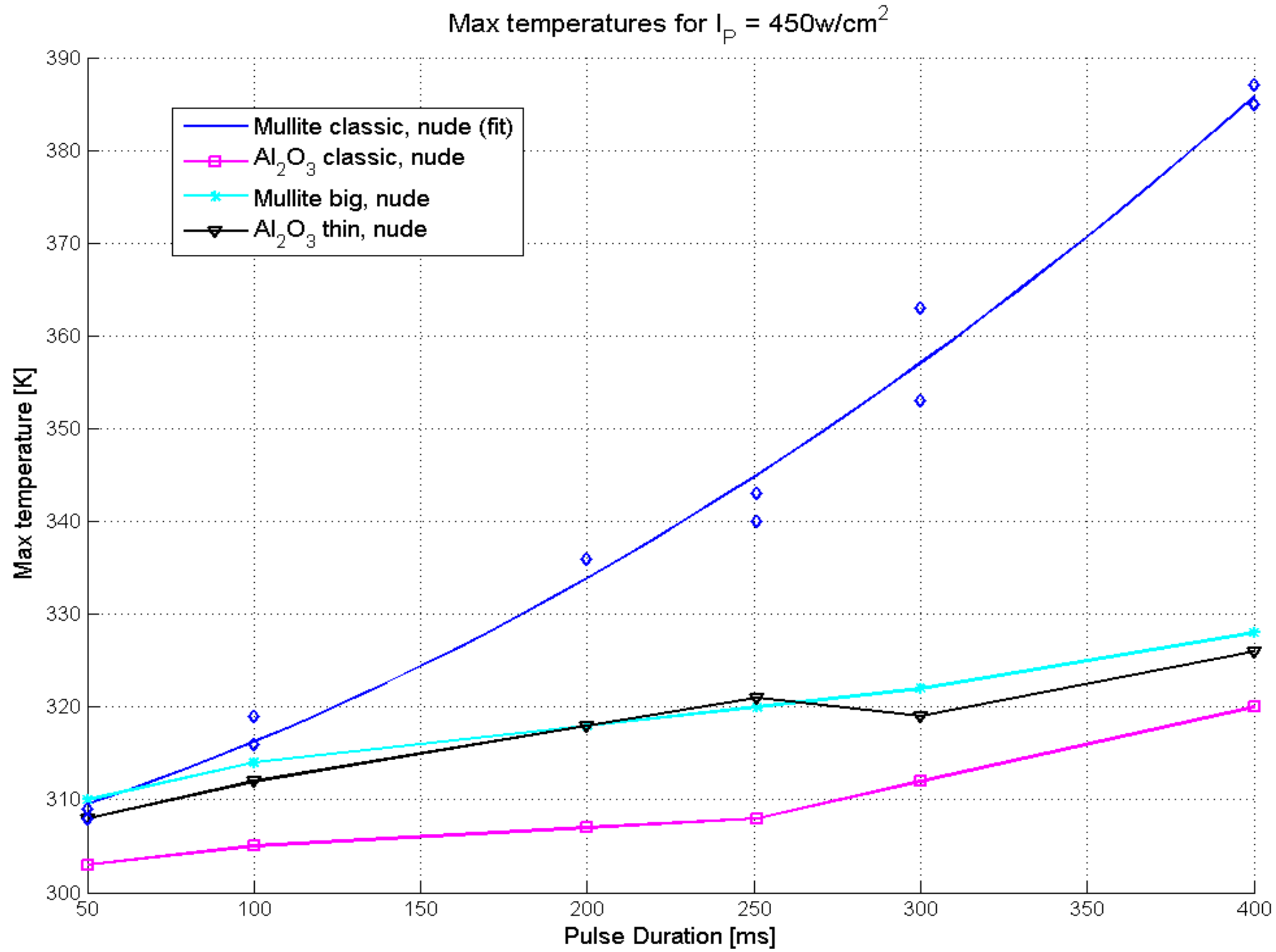




Questions

Backup slides

Bare tube absorption



"Mullite classic" absorbs better than the other tubes: This behavior is expected as it is composed of 80% mullite & 20% glass (glass is an absorber).

Overall, the tubes' absorption on their own is negligible.

Non-uniform HX illumination

All channels same diameter

Optimally tapered channel diameters

	Fixed Channel Diameter	Variable Channel Diameter
Outlet <T_t> (K)	1,521	1,700
I_{sp} (sec)	91	97
Thrust (N)	21	19
mdot (g/s)	23	20
No. of channels	191	233
Mass of channels (g)	670	570
Areal density (kg/m^2)	3.7	3.2

Decision: Fixed channel diameter good enough for now. Variable channel diameter model deferred.